TECHNICAL DESCRIPTION OF THE FACILITY

Due to strong demand and limited availability of beam time in solid-state spectroscopy, a dedicated beamline is proposed to fill-in the gap. This new beamline is planning to be located at sector 4 of Advanced Light Source (ALS), Lawrence Berkeley National Laboratory, sharing the same straight section with adjacent undulator beamline 4.0.2.

The major requirement for this beamline is to cover photon energies from ~20eV to 120eV, while at the same time delivering unprecedented energy resolution with reasonable photon flux (around 10^{11} photons/second). The targeting energy resolution is around 1meV. The choice of photon energy range is mainly driven by experimental constraints: the lower end needs to overlap with emission lines from discharge lamps, which can then be used for consistency check. Since the most common one is the He-Iα emission line (21.22eV), 20eV is the targeting photon energy; the upper end is chosen to cover the p levels (3p and/or 4p) of the transition metal oxides and partly the d levels of actinides (the f electron systems). These materials, which exhibit fascinating phenomena such as high-temperature superconductivity, colossal magnetoresistance (CMR) effect, Kondo effect, Mott metal-insulator transitions … etc, have been the most active research topics in condensed matter physics in the past century. They are expected to play the central roles both in future technology and physics and the operation of this beamline would greatly benefit the researches.

The following sections shortly describe the concept and design of this meV-resolution beamline.

UNDULATOR SOURCE

In order to accommodate two undulators with different periods in a straight section, a chicane system is used. The schematic plot of chicane system is shown in figure 1. The electron beam is first deflected towards the storage ring by a short steering magnet in front of the straight section. After passing the first undulator, the electron beam is deflected away by a dipole magnet at the center of the straight section and enters the second undulator. After passing through the second undulator, it is then deflected towards the ring and resumes its nominal trajectory. This concept was pioneered by the ALS accelerator physicists and has been successfully applied in the elliptically polarized undulator (EPU) beamline (BL 4.0.2) at sector 4.0.

The proposed undulator will have an 80mm magnetic period. The length of magnetic period is relatively short because at low photon energies, large K values make it more like a wiggler than an undulator. Thus the radiated power needs to be handled carefully. Albeit this disadvantage, certain useful aspects can be obtained with such choice: First of all, the full polarization control is possible (i.e. make this undulator an EPU). The EPUs with 50mm magnetic period have been successfully constructed and operated in the third generation light sources (for example, beamline 4.0.2 at the ALS). However, it has low energy cutoff around 87eV (57eV) when storage ring energy is 1.9GeV (1.5GeV). For other modes, such as vertical, elliptical and circular polarization modes, the cutoff energies are even higher[1]. In order to bring down the cutoff photon energies to meet our requirement, a longer magnetic period is required.

With geometrical dimensions of an 80 mm period and a 14mm magnetic gap, the insertion device is capable of producing linear polarized radiation in any plane containing the beam axis and

[1] With 1.9GeV storage ring energy, the cutoff energies are 183eV for vertical polarization mode, 98eV for elliptical polarization mode and 139eV for circular polarization mode. With 1.5GeV storage ring energy, the cutoff energies are 114eV for vertical polarization mode, 61eV for elliptical polarization mode and 87eV for circular polarization mode.

elliptically or circularly polarized radiation of either handedness. Energy range attainable in the various modes is:

- 12eV - 1700eV linear polarized (horizontal plane), using harmonics 1-5
- 22eV - 1700eV linear polarized (vertical plane), using harmonics 1-5
- 13eV - 1600eV elliptically polarized (either handedness), using harmonics 1-5
- 17eV - 420eV circularly polarized (either handedness), using the on-axis fundamental

Various methods are under consideration for attenuating the radiation of undesired harmonic wavelengths. These include optical absorption of higher harmonics on grazing mirrors and wavelength selectability coupled with higher 'harmonic' rejection in the monochromator. The latter technique derives from the introduction of quasi periodicity or other features of the undulator, which make higher energy radiation peaks not integers of the fundamental. The effect of the specialty operational modes (those other than the conventional horizontally linearly polarized mode) on electron beam dynamics is currently under study[2].

Changing the undulator period length is expected to affect the beam stability control. To be conservative, this new EPU will be operated in linear polarization mode in early stage of operation. During the construction/commissioning period, R&D projects will be launched in parallel to study the physics of this 80mm undulator design. Full elliptical and circular polarization modes will be resumed after a clear understanding is available.

Another reason for choosing an 80mm period is related to the total flux, brightness and power loading issues. Since the available space is merely 2 meters, a shorter period insertion device (say instead of 100mm period) will have more periods and will deliver higher flux and brightness.

The performance of a regular undulator can be calculated. The on-axis flux (in units of photons·(second)$^{-1}$·(0.1%BW)$^{-1}$) integrated over the central cone is:

$$F_n = 0.716 \times 10^{14} N Q_n I[A] \qquad (1)$$

N is the number of magnetic periods, I is the beam current (in Ampere), n is the harmonic order and Q_n is a combined Bessel function. This formula gives the flux at "exact harmonic frequencies", which will be used to calculate the power loading on optics. The spectral brightness B_n, which is defined as the number of photons per unit phase space volume, is:

$$B_n = \frac{F_n}{(2\pi)^2 \sigma_{Tx}\sigma_{Ty}\sigma_{Tx'}\sigma_{Ty'}} \qquad (2)$$

$\sigma_{Tx,y}$ is the standard deviation (std) of photon beam size (at source) in the horizontal and vertical directions and $\sigma_{Tx',y'}$ is the std of beam divergence[3, 4]. Figure 2 shows the calculated performance of a regular 80mm undulator (1st harmonic only) when storage ring energy is 1.9GeV and the beam current is 400mA. Other storage ring parameters are as follow: σ_x=310μm, σ_y=23μm, $\sigma_{x'}$=23μrad, $\sigma_{y'}$=6.5μrad and the total number of periods is 25. Throughout the desired energy

[2] From Ross Schlueter and Steve Marks.

[3] The photon beam size and divergence are root-mean-square of electron beam emittance and diffraction-limited beam size/divergence. See footnote 4.

[4] X-ray data booklet, LBL/PUB-490, edited by Center for X-Ray Optics (CXRO) and Advanced Light Source (ALS). K.-J Kim, Optical Engineering, vol 34, p. 342 (1995). The formula used in the calculation are from K.-J. Kim, which give half of the value quoted in X-ray data booklet.

range, this undulator delivers the flux on the order of 10^{15} photons/second-0.1%BW and the brightness around 10^{17}photons/second-mm^2-mrad^2-0.1%BW. Such high flux and brightness are critical for high-resolution operations.

Because this meV-resolution beamline is designed to deliver low energy photons, most of the unwanted power coming mainly from high energy photons needs to be filtered out by first and second mirrors. The worst case would be the lowest photon energy, which is around 15eV. We have calculated the power integrated over the central cone for individual harmonic. This power (for each harmonic) is then transmitted through individual optics and is corrected by the mirror reflectivity (for mirror angles, see later discussion). The difference between in-coming and transmitted power is the absorbed power for each optical element. Once this is known, the on-axis power density (total) can be obtained by dividing out the central cone size for each harmonic under proper demagnification and sum them up. The obtained power densities are as follow (for notation, see optical layout in figure 3):

- M1: 62.77 W/mm^2
- M2: 2.08 W/mm^2
- M3: 0.31 W/mm^2
- After M3 to G1, M4 and M5: <0.04 W/mm^2

Since these mirrors are not normal to the beam trajectory, the projection of the central cone on the mirror surface needs to be considered. This brings down the power densities on the optics:

- M1: 1.81 W/mm^2
- M2: 0.22 W/mm^2
- M3: 0.08 W/mm^2
- After M3 to G1: <0.01 W/mm^2

These values are quite common compare to other beamlines at ALS, thus the standard water-cooling mechanism will be used in the design of M1 and M2 mirror carriages.

BEAMLINE

A standard beamline includes a front end, optics (mirrors and gratings) and one or more branch lines. The front end of this meV-resolution beamline will be the same as other beamlines. It consists of individual photon stops (PS), horizontal and vertical beam defining apertures (H/V BDA) and personnel safety shutter. The PSs and H/V BDAs have integral water-cooling systems to withstand high power and power density of the undulator radiation and will be used in conjunction with the standard ALS equipment-protection system (EPS).

PRE-MIRRORS

The schematic plot of this meV-resolution beamline is shown in figure 3. It contains the following components (from upstream to downstream):

1. A horizontal deflection mirror (M1) with horizontal (tangential direction) focusing at the entrance slit.
2. A horizontal deflection mirror (M2) with vertical (sagittal direction) focusing at the entrance slit.
3. A nearly stationary entrance slit (S1) with +/- 2” motion.
4. A vertical deflection plane mirror (M3) to compensate the beam height.
5. A set of spherical gratings (G1).

6. A nearly stationary exit slit (S2) with +/- 2” motion.
7. Two horizontal deflection mirrors (M4-1 and M4-3), which deflect the beam into two branch lines and focus it horizontally (tangential direction) at the experimental endstations.
8. Two vertical deflection mirrors (M5-1 and M5-3) with vertical (tangential direction) focusing at the experimental endstations.

The first two mirrors, M1 and M2, will have standard water-cooling mechanism. For the plane mirror (M3) and gratings (G1), water-cooling will be used to reduce thermal distortion on the optics profile. But for the rest of optics (M4 and M5), there will be no cooling mechanism.

The plan view and side view of this beamline are shown in figure 4 and 5. In order to minimize the cost and interference to adjacent beamline, the first mirror M1 will utilize the existing mirror tank and the mounting mechanism. Under current design, M1 deflects the beam outbound by 3.3^o (total deflection angle). It has cylindrical profile and focuses the beam horizontally onto the entrance slit. The required mirror radius is approximately 298.38m and the footprint is around 50cm (L) by 1.5cm (W)[5].

The distance between source (taken at the center of undulator) and M1 is 11.12m. The entrance slit is 7.00m away from M1, this gives a horizontal demagnification ratio around 1.59. Since it has to transmit low energy photons and has to filter out excess power, carbon coating will be used.

With a merely 3.3^o deflection angle, the separation between this beamline and BL 4.0.2 is too small. It requires another outbound deflection to open up the space. This is done by inserting second cylindrical mirror M2, which deflects the beam 12^o outbound. The distance between M1 and M2 is set to be 4.2m. With it, the space is big enough for inserting water-cooling and mounting mechanism into M2 mirror tank. M2 uses sagittal focusing to focus the beam vertically onto the entrance slit. The required mirror radius is approximately 0.495m. Because of sagittal focusing, the beam height will not be changed, which is a big advantage in aligning the whole beamline.

The footprint on M2 is approximately 6cm (L) by 2cm (W). The entrance slit is 2.8m away from M2, thus the vertical demagnification ratio is around 5.47. In design, M2 should also have carbon coating on it to maximize the transmission.

VARIABLE INCLUDE ANGLE SPHERICAL GRATING MONOCHROMATOR

Since the monochromator has to deliver photons with energies between 20eV and 120eV, the normal incident monochromator (NIM) design is excluded due to its high energy cutoff around 30eV. One ideal choice would be the spherical grating monochromator (SGM) design, which is very common for UV/soft X-ray beamlines. Three gratings are needed to cover the full photon energy range. The high-density grating is designed to cover photon energies between ~60-120eV and the mid and low-density gratings are for 30-60eV and 15-30eV. The specs for mid and low density gratings can be obtained via scaling law. The choice of photon energy range sets the horizon wavelength around 300Å and the included angle 150^o is chosen based on the reflectance consideration. The overall length (see green area in figure 4) measured from entrance slit to exit

[5] The footprint of each mirror is calculated at 15eV by using SHADOW. The beam divergence and size are taken only for first harmonic since the first harmonic central cone is the largest among all other harmonics. At this photon energy, the beam size and divergence are also the largest among other photon energies.

slit is approximately 7.7m. The Rowland condition needs be satisfied throughout the whole energy range to achieve the desired 1meV energy resolution.

Small include angle poses a major concern in positioning the gratings and downstream optics. If the downstream optics are intended to be placed at nominal height (around 1.2m), the grating tank will be sitting at extreme location, which is either too high or too low. The related engineering design and monochromator stability issue will be too hard to manage. Thus another deflection optics, a plane mirror M3, is used to compensate the deflection angle and brings the out-going light back to horizontal. M3 deflects the beam 30^{o} downward and the outgoing photon beam becomes parallel to the floor at approximately 1.25m above the floor (see figure 5).

Adding M3 opens up the possibility of varying the include angle. Since M3 can be translated and rotated separately from gratings, the include angle can be slightly varied and the on-blaze condition can be partially fulfilled to achieve higher grating efficiency. Furthermore, the incoming and outgoing beams are parallel to each other and also parallel to the ALS floor. The grating tank can be translated along the beam trajectory to fulfill the Rowland condition, while at the same time, both entrance and exit slits remain nearly stationary. This has the following advantages:

1. Because the whole grating tank is moving, the monochromator stability issue becomes easier to handle.
2. The position of the gratings can be reliably reproduced because of increased monchromator stability.
3. The design of grating tank can be simplified by adopting the of SX700 monochromator in MES project. This reduces the cost of the project.
4. To fulfill the Rowland condition, the entrance slit can be kept stationary while the exit slit moves no more than 2”. Thus M1 and M2 can be made non-adaptive. This is critical because of great uncertainty in making a water-cooled, large curvature (small mirror radius) mirror adaptive.
5. The exit slit only needs to move approximately +/- 1” (assuming the entrance slit is fixed, see figure 6 for the variation in the separation between both slits) to track the Rowland condition. Thus it is relatively easy to adjust the curvature of M5 mirror to maintain focusing on the sample. The bender mechanism can be simplified.
6. If the exit slit is fixed and the entrance slit moves by +/- 1”, the slit is still within the focal depth of M2. Now one is able to achieve sub-micron focusing with zone plate and the source broadening issue is gone (the exit slit is used as the source of zone plate, which is fixed in this case). This opens up the possibility of performing spatially resolved spectroscopy.

The footprint on M3 is around 4cm (L) by 0.3cm (W). In order to compensate the translation of grating tank, the actual width needs to be increased. Also the coating needs to be specially made: the portion that couples to high density grating should have Au coating on it to achieve higher reflectivity, but the rest of it should have carbon coating.

The energy resolution of this monochromator design is mainly determined by slit size (both entrance and exit slits) and slope error. This is shown in theoretical calculations done by Malcolm Howells. Figure 7 shows the contribution from three major aberrations: spherical aberration (red markers), primary coma (blue markers) and line curvature (green markers). The full width of beam divergence used in the calculation is 1mrad in both tangential and sagittal planes and the beam size is 10μm in the tangential plane. It is clear that these aberrations only contribute up to 0.1meV in energy resolution, which is negligible in reality. The slit-limited resolution (meV per μrad), which scales linearly with the ratio of line spacing d and Rowland radius R, d/R, is one major contribution to energy resolution. This means higher ruling density gives higher energy resolution. The ruling densities of these three gratings are chosen to be 3,600, 1,800 and 900 lines/mm respectively to achieve the resolution with ~5µm source. Another contribution is from the slope error. The calculated slit-limited resolution (red markers) and the slope error (blue markers) for 3,600lines/mm high-density grating are shown in figure 8. In order to achieve 100,000 resolving power, both entrance and exit slits need to be kept below 5µm and high quality substrate with slope error better than 0.5µrad is required.

With these numbers, the calculation shows a resolving power of approximately 100,000 with 5µm slits and 60,000 with 10µm slits at 120eV (see figure 9). The resolving power increases rapidly when approaching lower end of the photon energy range. At 60eV, the theoretical value is higher than 200,000. The corresponding energy resolution is around 300µeV. Although the resolving power for mid- and low-density gratings is the same as high-density grating, the energy resolution will scale down with photon energy. Thus achieving energy resolution around 1meV is practical.

In conjunction with these three gratings, three more gratings with slightly lower ruling densities, 2,400, 1,200 and 600 lines/mm, will be used to cover the same photon energy ranges. The hope is to gain some grating efficiency in the expenses of a slightly lower resolving power (down by approximately 30%). Thus users are able to operate this beamline in either high-resolution or high-efficiency modes, depending on their experimental requirements. Since the footprint on the gratings is not large, roughly 8cm (L) by 0.4cm (W), it is possible to have two or three different ruling and coating on a single substrate. The grating interchange mechanism can also be simplified. We intend to slide the whole grating tank transversely relative to the beam as a way to change gratings. This mechanism gives better reproducibility and stability and it also allows us to utilize the current MES monochromator design. There will be encoder system to track the grating tank position, as well as the angles of gratings.

BRANCH LINES

In the downstream, there is a mirror tank (mirror switching yard) with two horizontal mirrors to deflect and focus the beam into two branch lines (4.0.1.1 and 4.0.1.3). The schematic plot of this section is shown in figure 10. Two branch lines are dedicated to spectroscopy and the middle one is reserved for users' roll up systems.

The horizontal deflection/focusing mirror M4-1, which deflects the beam 16^o outbound into the branch line 4.0.1.1, is 3.5m away from the exit slit. It takes the entrance slit (11.2m away) as the source and focuses it horizontally onto the endstation that is 2.5m further downstream. The calculated mirror radius is approximately 29.37m and the horizontal demagnification ratio is approximately 4.48. Hence the combined horizontal demagnification is around 7.12. The footprint on M4-1 is approximately 20cm (L) by 2cm (W).

Another mirror, M4-3, is the same as M4-1 in current design. These two mirrors will be sitting at a translation stage which moves them transversely relative to the beam. Thus photon beam can be deflected into different branch lines depending on which mirror it hits. If these two mirrors are out of way, the beam is delivered down to the middle branch line (4.0.1.2) without any deflection.

1.5m away from M4 mirror tank is the M5-1 mirror tank (same for M5-3 mirror tank, see figure 10). This mirror deflects the beam downward by 10^o. It takes the exit slit as source and focuses it vertically onto the endstation that is 1m away. In order to achieve optimal focusing, M5-1 is designed to be adaptive to account for exit slit motion and has elliptical profile. The vertical demagnification ratio, in this design, is approximately 5. Thus the overall vertical demagnification ratio is 27.35. The footprint on M5-1 is around 25cm (L) by 0.8cm (W) (same for M5-3). The separation between M5-1 mirror tank and M5-3 mirror tank is around 82cm.

The first branch line (4.0.1.1) is reserved for high-resolution UV light scattering spectroscopy. The endstation is 1m away from M5-1 mirror tank. The photon beam size on the sample, with total demagnification ratio 7.12 in horizontal direction and 27.35 in vertical direction, varies from 100μm (H) by 1μm (V) (around 120eV) to 100μm (H) by 2μm (V) (around 20eV)[6].

The third branch line (4.0.1.3) is reserved for high-resolution angle-resolved photon emission spectroscopy. Since the endstation is also 1m away from M5-3 mirror tank, the photon beam characteristic will be identical to branch line 4.0.1.1. The separation between these two endstations is around 1.4m.

RAY TRACING RESULTS

We have performed the ray tracing by using SHADOW® to test the conceptual design parameters and the results are shown in figure 11. In this simulation, the grating is assumed to be free from any imperfection.

This figure shows the images at the exit slit plane at three different photon energies: around 124eV (top panel), 62eV (middle panel) and 31eV (bottom panel). The first two sets are calculated with the grating ruling density 3,600 lines/mm and the last one is with 1,800 lines/mm. The source is taken as the rectangular image of the entrance slit, with spot size equal to the real photon beam (+/- 1$\sigma_{x,y}$) under proper demagnifications. In each set, two photon energies are used: (top panel) 123.9842eV (black) and 123.9855eV (gray). The energy separation is 1.3meV; (middle panel) 61.9921eV (black) and 61.9927eV (gray). The energy separation is 0.6meV; (bottom panel) 30.9960eV (black) and 30.9964eV (gray). The energy separation is 0.4meV. In each panel, it is clearly seen from the side histogram that the two energies are well separated with peak separations much larger than the half-width. The overall resolving power is on the order of 100,000 and it becomes better when the photon energies are lower. Thus this varied include angle SGM design indeed delivers the energy resolution better than 1meV.

THROUGHPUT OF THE BEAMLINE

One major concern about the high-energy resolution beamline is the throughput. Ideally, the energy resolution can be greatly improved if both entrance and exit slits are reduced concurrently. However, the photon flux on the sample will be dramatically reduced also. Thus it is critical to know the flux on the sample when beamline parameters are set at practical values. In general, the throughput of a beamline can be calculated if the following parameters are known:

1. Merit photon flux of the undulator.
2. Reflectivity of various mirrors.
3. Efficiency of gratings.
4. Transmission of whole beamline with preset optics sizes.

The overall throughput is the product of these terms.

[6] The number quoted here is full width at half-maximum (FWHM).

The flux and brightness of an 80mm undulator are shown in figure 2. Within interested photon energy range, the flux is around 10^{15} photons/second-0.1%BW and the brightness is approximately $6*10^{17}$ photons/second-mm^2-mrad^2-0.1%BW.

The overall reflectivity of five mirrors is calculated by assuming that M1, M2, M4 and M5 have carbon coating. As for M3, due to dramatic loss in reflectivity above 80eV (with 30^o total deflection) for carbon coating, Au coating is used instead. The reflectivity of all mirrors is shown in figure 12, which is obtained by multiplying the reflectivity of individual optics together. Throughout the photon energy range, it varies from ~30-45%[7].

Since these gratings have constant line spacing, making them holographic gratings would be more ideal (price wise and efficiency wise) than blazed gratings. The performance of a holographic grating depends strongly on the groove depth and width and they need to be optimized to achieve optimal efficiency. We have used Neviere's code (the electromagnetic code) to calculate the efficiency of mid- and high-density gratings with various combinations of groove width and depth. In the calculation, the mid-density grating (1,800 lines/mm) has carbon coating while the high-density grating (3,600 lines/mm) has Au coating for higher efficiency. The calculated grating efficiency is shown in figure 13. The ruling profiles are as follow: for high-density grating, the groove depth is 140Å and width is 1,900Å; for mid-density grating, the width is 3,800Å and the depth is 3,800Å. Under such conditions, the high density grating efficiency (60eV-120eV) is between 8-17% and mid density grating efficiency (30eV-60eV) is between 15-24%.

The transmission of beamline depends strongly on the accepted phase space volume. It is determined by the geometry of beamline, sizes of optics (mirrors and gratings) and slits. Ideally, one would like to accept all central cone (first harmonic) to maximize the throughput, however it might be impractical due to unreasonably large optics or slit sizes. Thus the optics and slit sizes are set to reasonable values during the calculation. We have used SHADOW to calculate the transmission of the whole beamline with following optics/slit size (for summary, see Appendix A):

- M1: 40cm (L) by 10cm (W)
- M2: 10cm (L) by 5cm (W)
- M3: 20cm (L) by 20cm (W)
- G1: 20cm (L) by 4cm (W)
- M4-1 and M4-3: 20cm (L) by 4cm (W)
- M5-1 and M5-3: 20cm (L) by 4cm (W)

Entrance and exit slits are set corresponding to either 1meV energy resolution or 100,000 resolving power (RP) and 0.25μrad or 0.5μrad slope error. For high density grating, the slit sizes vary from ~10μm (~60eV) to ~5μm (~120eV) for RP 100,000 and from ~17μm (~60eV) to ~3μm (~120eV) for 1meV resolution. For mid density grating, the slit sizes vary from ~10μm (~30eV) to ~5μm (~60eV) for RP 100,000 and from ~38μm (~30eV) to ~8μm (~60eV) for 1meV resolution. We also calculate the throughput with fixed 5μm and 10μm slits. With these slit and optics settings, the transmission of whole beamline is obtained by using SHADOW to observe beam loss from source to sample positions. The throughput is shown in figure 14. As expected, the throughput with 0.5μrad slope error is slightly lower than the one with 0.25μrad.

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[7] The reflectivity of mirrors is calculated down to ~30eV, which is the limit of the reflectivity code. In this case, only the throughput of mid and high density gratings are calculated.

For high density grating (3,600 lines/mm), the throughput varies from ~30% to ~60% with RP equal to 100,000 (red and blue markers). It varies from ~20% to ~85% with 1meV energy resolution (pink and black markers). For mid density grating (1,800 lines/mm), the throughput varies from ~35% to ~55% with RP equal to 100,000 (red and blue markers). It varies from ~50% to ~100% with 1meV energy resolution (pink and black markers). The dramatic increase is due to much larger slit sizes.

With these numbers in hand, the photon flux on sample can be calculated. It is the product of those factors mentioned earlier. Furthermore, the corresponding bandwidth from undulator is corrected to account for unprecedented resolution. The overall results are shown in figure 15. In both panels, we are comfortable to say that the flux on sample is around 10^{11} photons/sec. This magic number, 10^{11} photons/sec, is the minimum requirement for a practical experiment.

In the near future, the performance of storage ring will be greatly improved to deliver higher brightness and more flux. In that case, the overall performance of the beamline will also be greatly improved due to some gains from source and overall transmission.

Appendix A: Optics parameters:

Parameters for optics, meV beam line at sector 4, version 5 1/1/03

Optical Element	Optics Type	Description	Coating	Total Deflection	distance (from previous optics,m)	distance (from source, m)		DeMagnification =u/v	Radius (m)	Mirros size (Footprint) (L*W, cm)	Power Loading (with projection) (W/mm2)	
M1	Cylinder	horizontal (tangential) focusing @ entrance slit	Carbon	3.3 deg outbound	11.12	11.12	(u,v)=(11.12, 7.0); θ=1.65 deg	1.59 (H)	298.3824995 (tan)	40*10 (50*1.5)	62.77 (1.81)	
M2	Cylindrical	vertical (sagittal) focusing @ entrance slit	Carbon	12 deg outbound	4.20	15.32	(u,v)=(15.32, 2.8); θ=6 deg	5.47 (V)	0.49490651 (sag)	10*5 (6*2)	2.078 (0.22)	
S1	Entrance Slit, +/- 2" motion				2.80	18.12						
M3	Plane	no focusing, deflects beam down	Au/Carbon	30 deg downward						20*20 (4*0.3)	0.309 (0.08)	
G1	Spherical Grating	deflects beam up	Au/Carbon	include angle 150 degree						20*4 (8*0.4)	<0.04 (<0.01)	
S2	Exit Slit, +/- 2" motion				7.7 (from entrance slit)	25.82						
M4-1	Cylindrical	horizontal(tangential) focusing @ ES1	Carbon	16 degree outbound	3.50	29.32	(u,v)=(11.2, 2.5); θ=8 deg	4.48 (H)	29.37055518 (tan)	20*4 (20*2)		
M4-3	Cylindrical	horizontal(tangential) focusing @ ES2	Carbon	16 degree inbound	3.50	29.32	(u,v)=(11.2, 2.5); θ=8 deg	4.48 (H)	29.37055518 (tan)	20*4 (20*2)		
M5-1	Elliptical Cylinder, bendable	vertical (tangential) focusing @ ES1	Carbon	10 degree downward	1.50	30.82	(u,v)=(~5.0, 1.0); θ=5 deg	~5 (V)		20*4 (25*0.8)		
M5-3	Elliptical Cylinder, bendable	vertical (tangential) focusing @ ES2	Carbon	10 degree downward	1.50	30.82	(u,v)=(~5.0, 1.0); θ=5 deg	~5 (V)		20*4 (25*0.8)		
ES1	End Station 1 (UV scattering)	UV scattering end station			1.00	31.82		7.12 (H); 27.35 (V)				
ES3	End Station 3 (ARPES)	ARPES end station			1.00	31.82		7.12 (H); 27.35 (V)				

Figures:

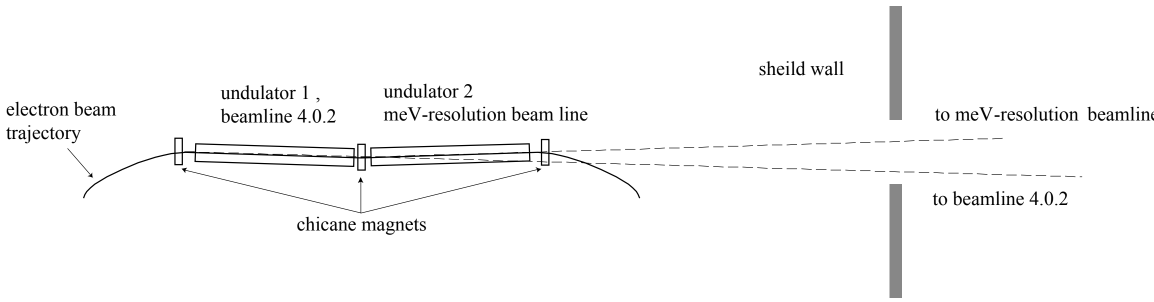


Figure 1: Schematic plot of chicane system at sector 4, Advanced Light Source (ALS).

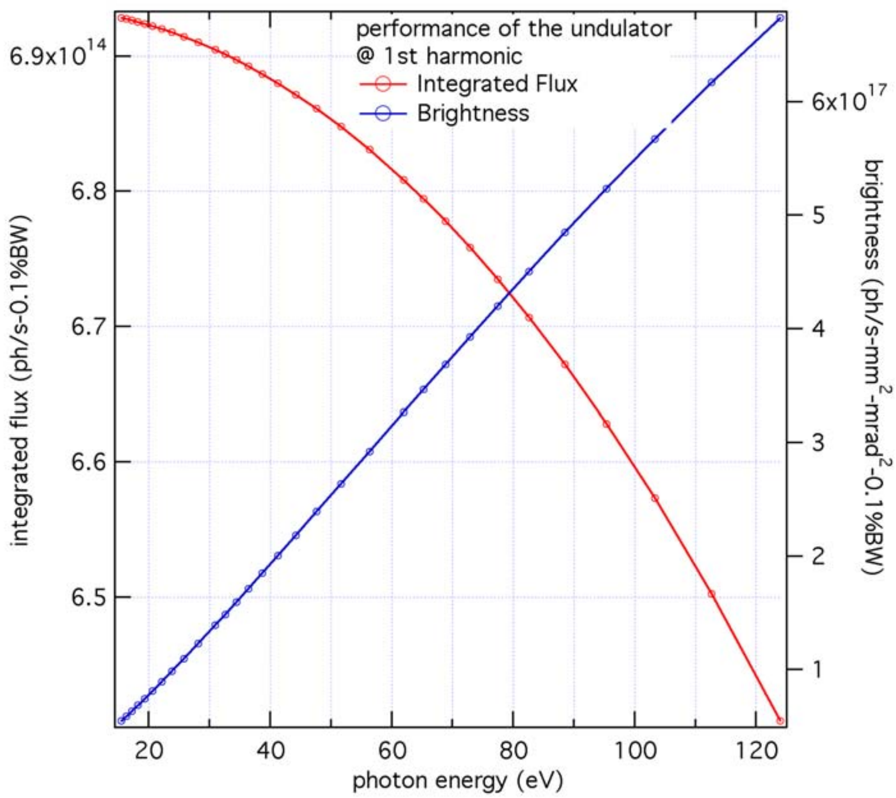


Figure 2: Performance of a regular 80mm period undulator at 1st harmonic. Red markers are the integrated flux over the central cone and blue markers are the brightness.

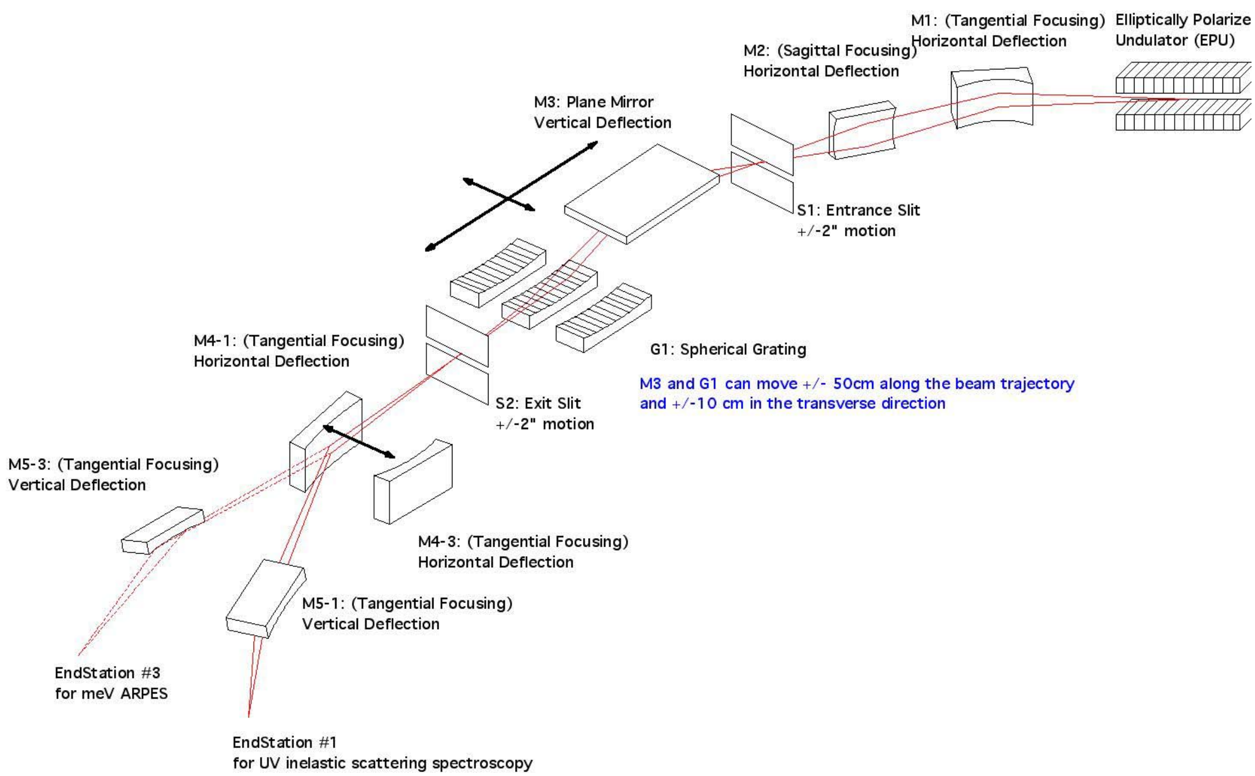
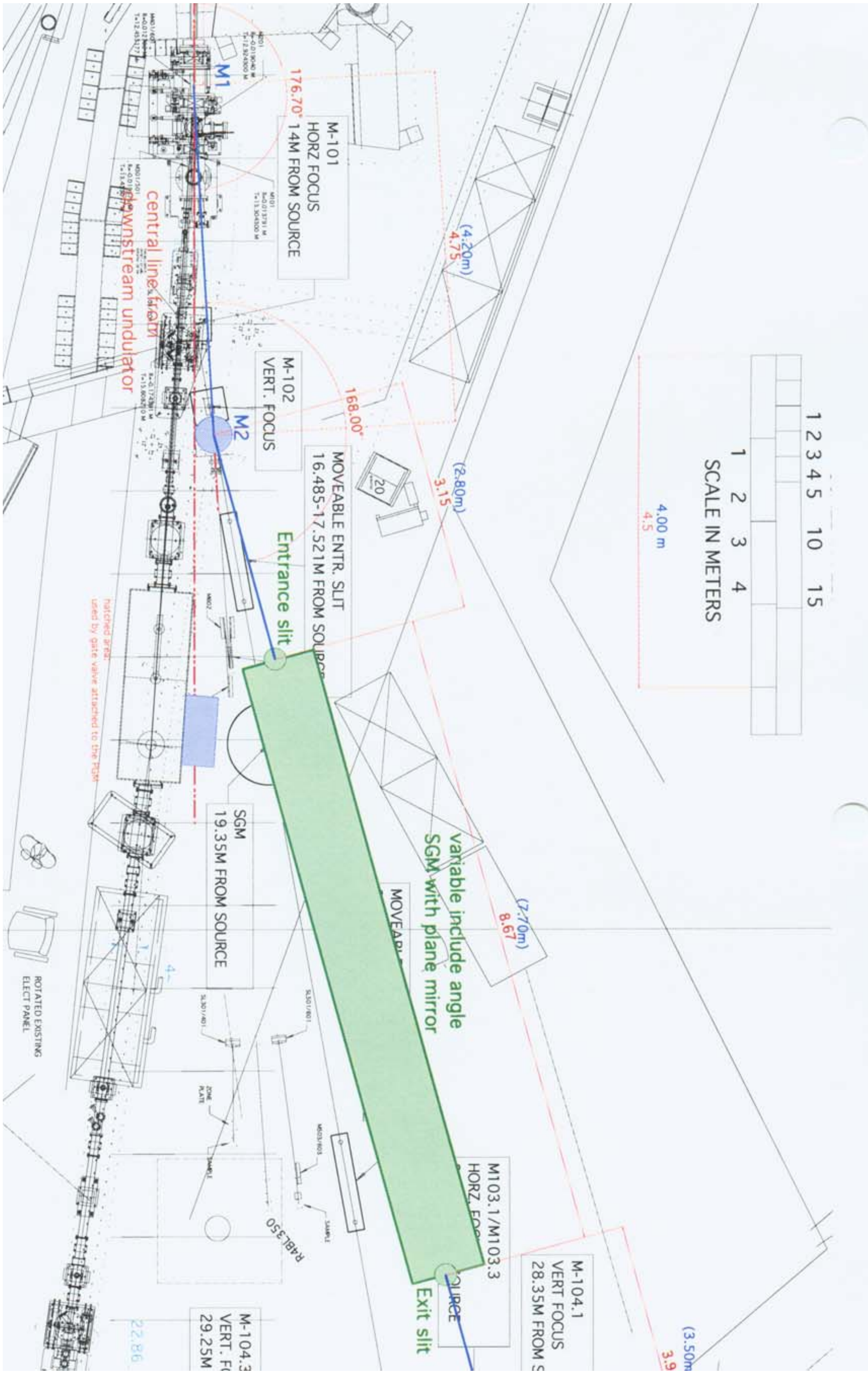


Figure 3: Optical layout of meV-resolution beamline at sector 4.


M1
M-101
HORZ FOCUS
14M FROM SOURCE
176.70°
central line from downstream undulator
M-102
VERT. FOCUS
M2
168.00°
MOVEABLE ENTR. SLIT
16.485-17.521M FROM SOURCE
Entrance slit
SGM
19.35M FROM SOURCE
variable include angle
SGM with plane mirror
M103.1/M103.3
Exit slit
M-104.1
VERT FOCUS
(4.20m)
4.75
(2.80m)
3.15
(7.70m)
8.67
4.00 m
4.5
1 2 3 4
1 2 3 4 5 10 15
SCALE IN METERS
ROTATED EXISTING
ELECT PANEL
RABL350

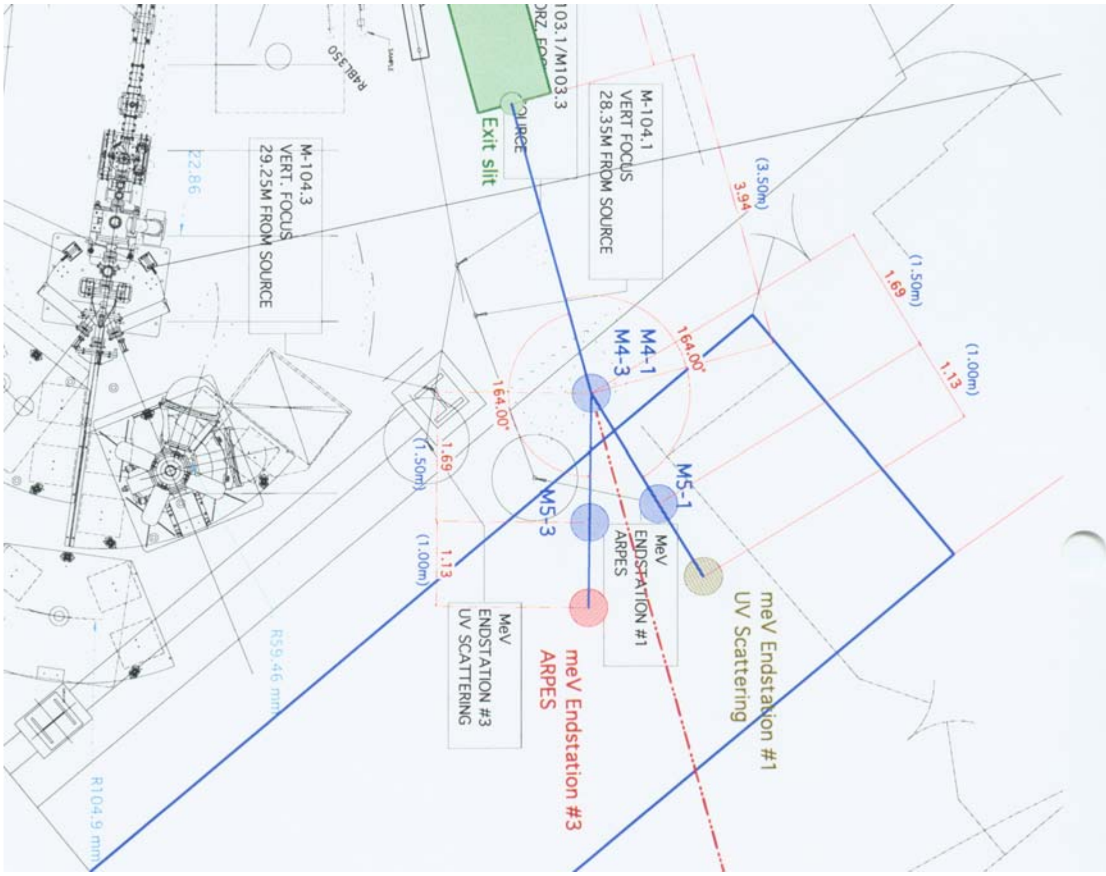


Figure 4: Plan view of the meV-resolution beamline. Green area indicates the space occupied by the monochromator.

QuickTime™ and a None decompressor are needed to see this picture.

Figure: 5: Side view of meV-resolution bealine. Black and red circles for M3/G1 indicate the lowest/highest photon energy positions.

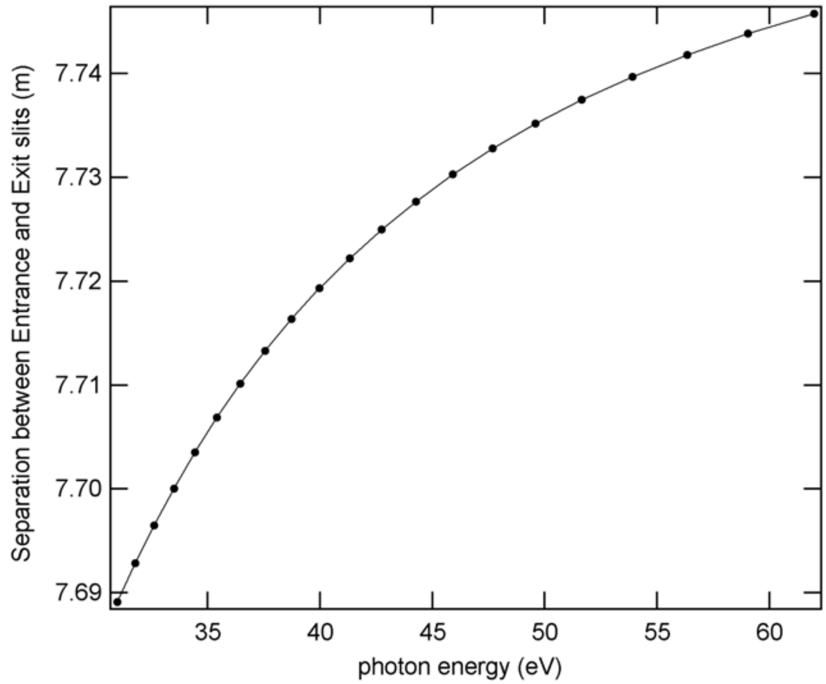


Figure 6: Separation between the entrance and exit slits when Rowland condition is satisfied.

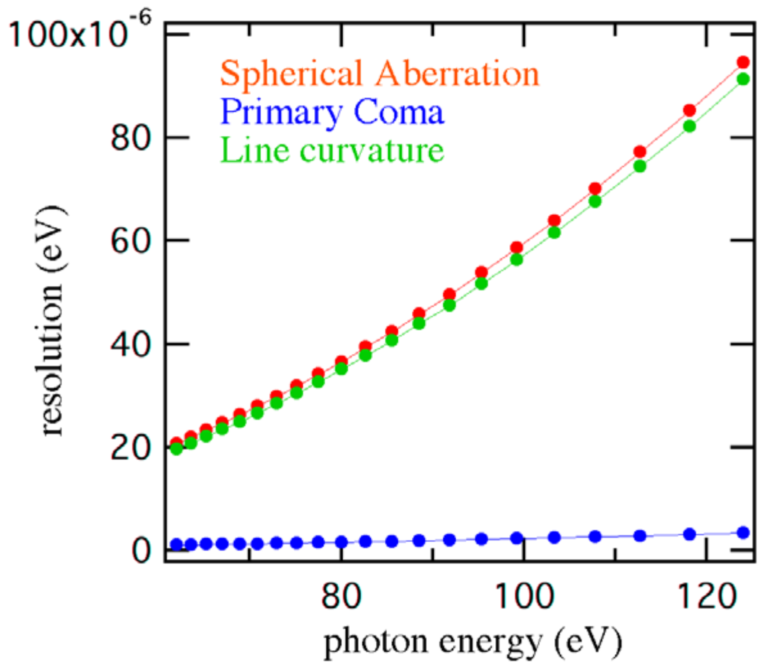


Figure 7: Resolutions from various aberrations: red markers: spherical aberration; blue markers: primary coma; green markers: line curvature.

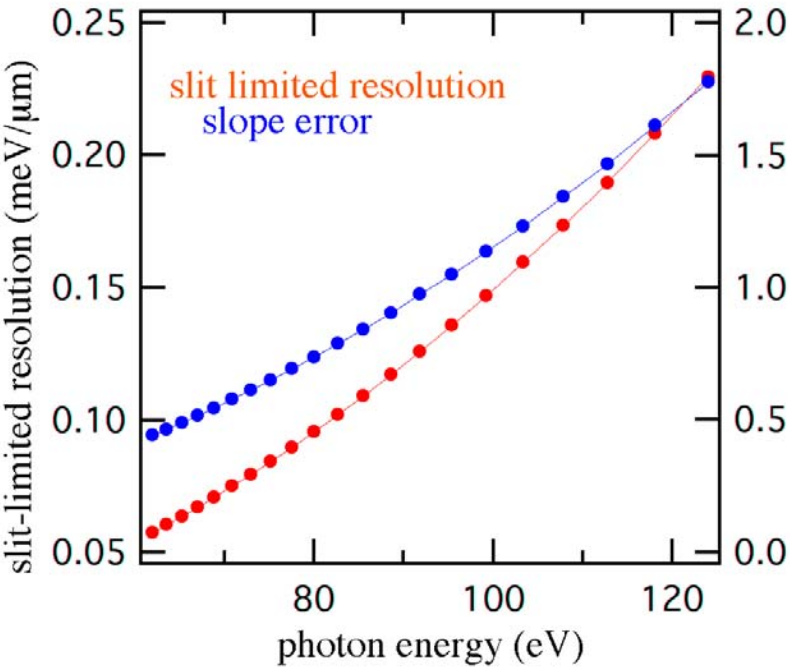


Figure 8: Resolutions from slits (red markers) and slope error (blue markers) for high density (3,600 l/mm) grating.

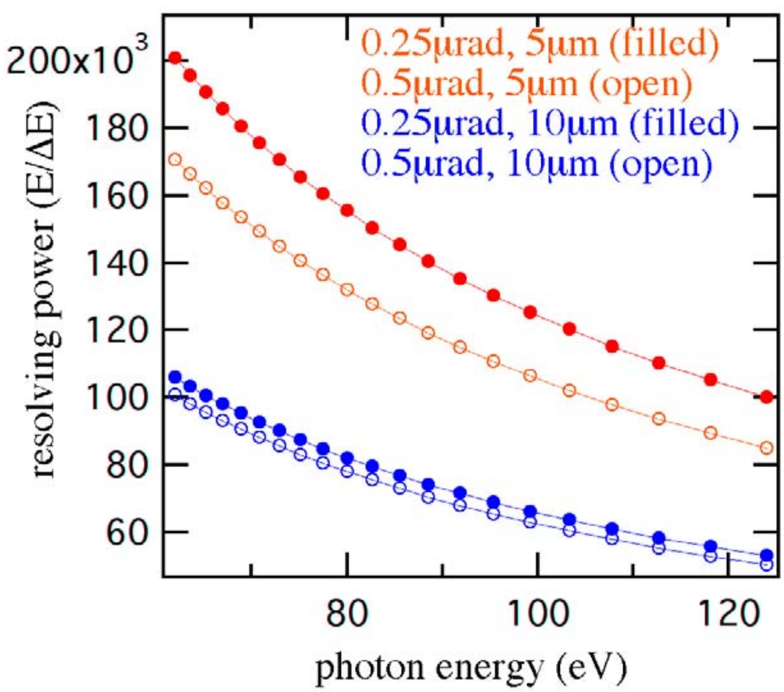


Figure 9: Theoretical resolving power (E/ΔE) for high density grating (3,600 lines/mm) with slope error 0.25μrad (filled) and 0.5μm (open) and slit size (both entrance and exit slits) 5μm (red) and 10μm (blue).

QuickTime™ and a None decompressor are needed to see this picture.

Figure 10: Schematic plot for mirror switching tank (for M4-1 and M4-3) and downstream optics.

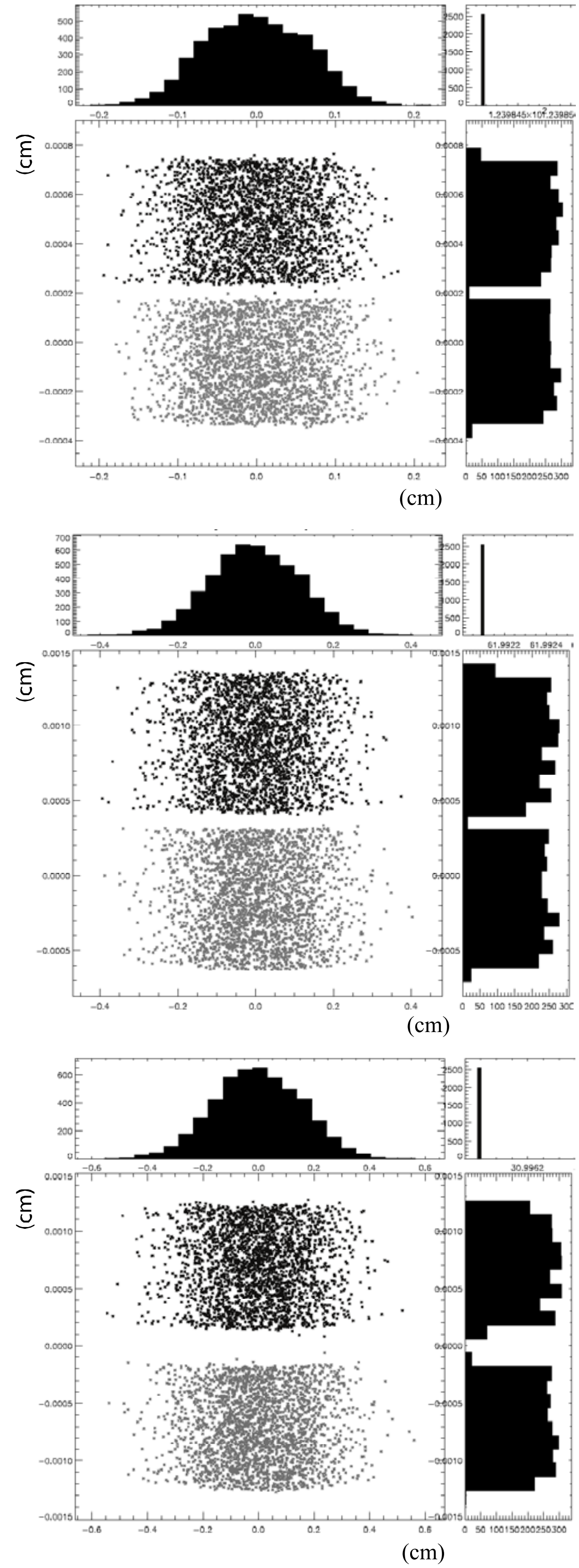


Figure 11: SHADOW simulation results at three photon energies: ~124eV (top), ~62eV (middle) and ~31eV (bottom).

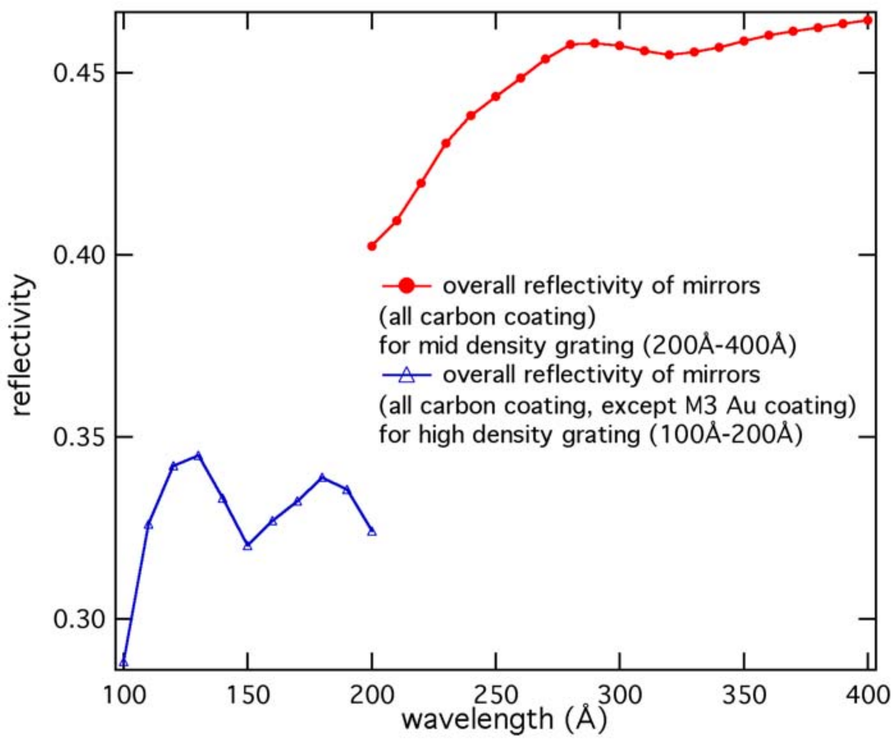


Figure 12: Overall reflectivity of five mirrors. Blue markers are for high density grating and red markers are for mid density grating.

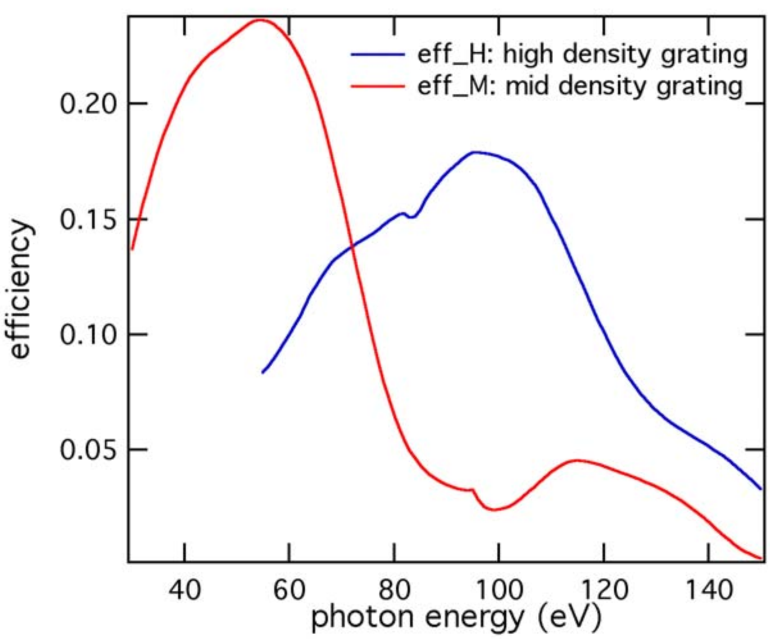


Figure 13: Theoretical efficiency of high density grating (blue line) and mid density grating (red line).

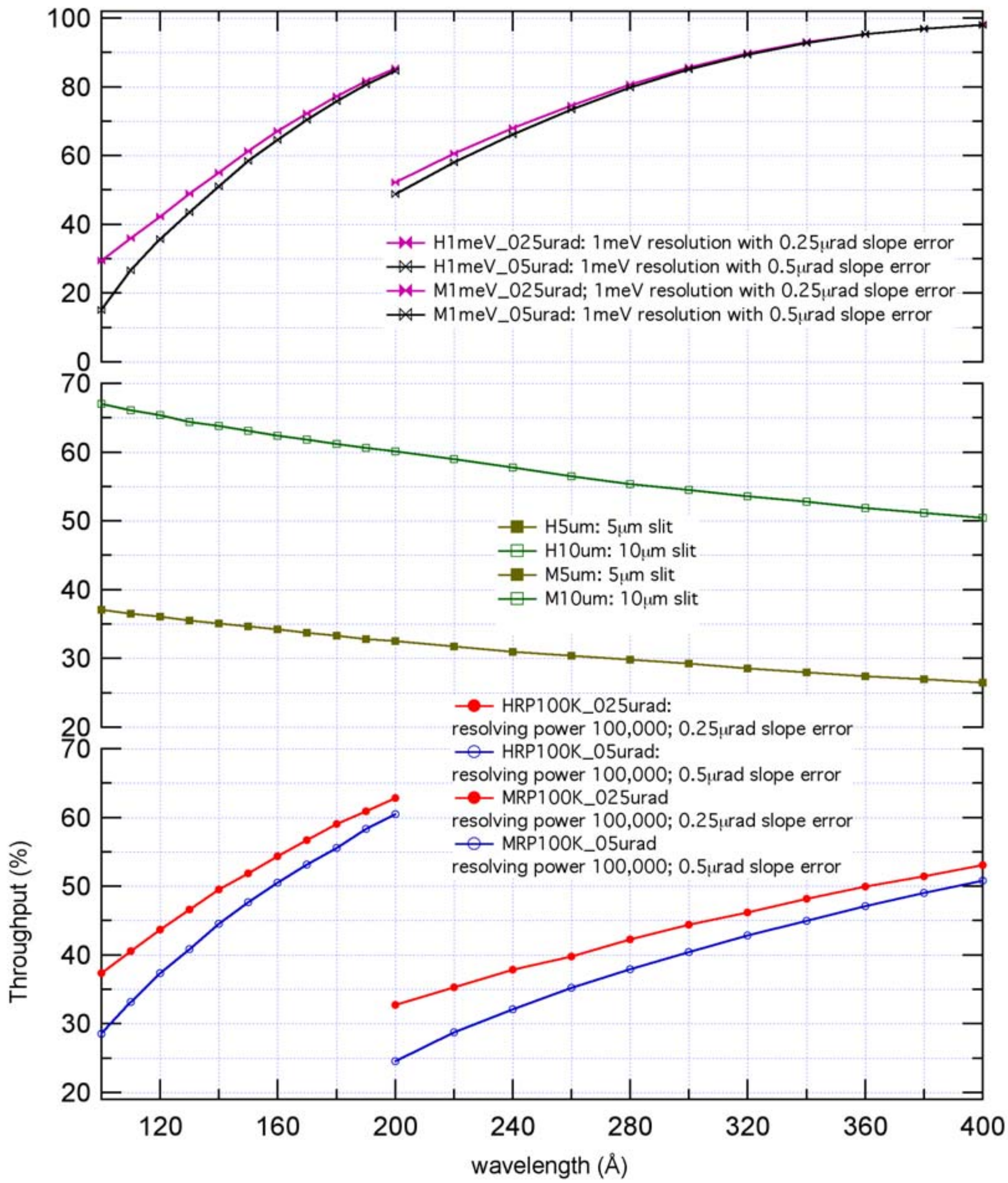
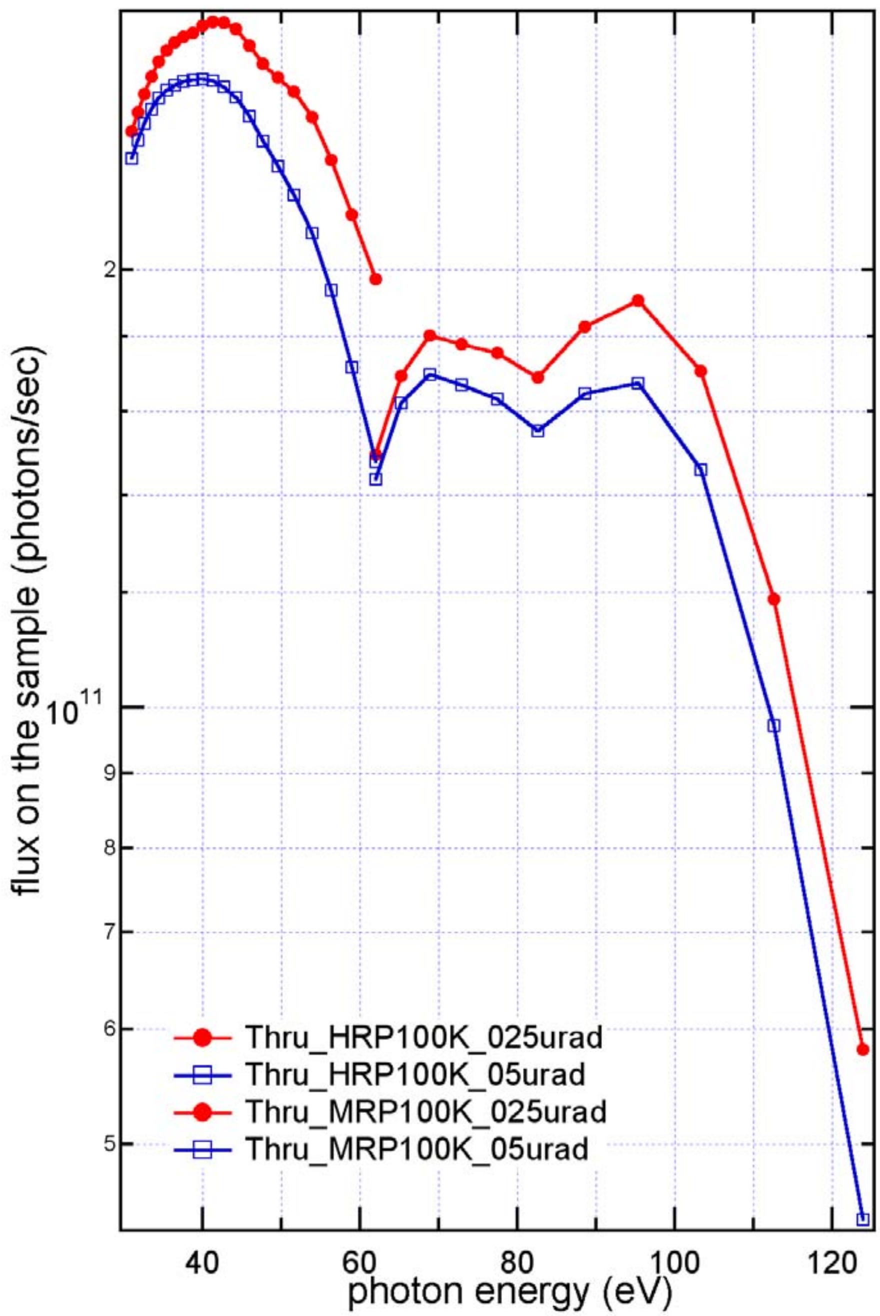


Figure 14: Throughput of whole beamline with various slits setting and slope error as a function of wavelength. For high density grating (100Å-200Å), the efficiency ranges from ~30% to 70-80% and for mid density grating (200Å-400Å), it ranges from ~25% to ~100%.



flux on the sample (photons/sec)
2
10^{11}
9
8
7
6
5
40
60
80
100
120
photon energy (eV)
Thru_HRP100K_025urad
Thru_HRP100K_05urad
Thru_MRP100K_025urad
Thru_MRP100K_05urad

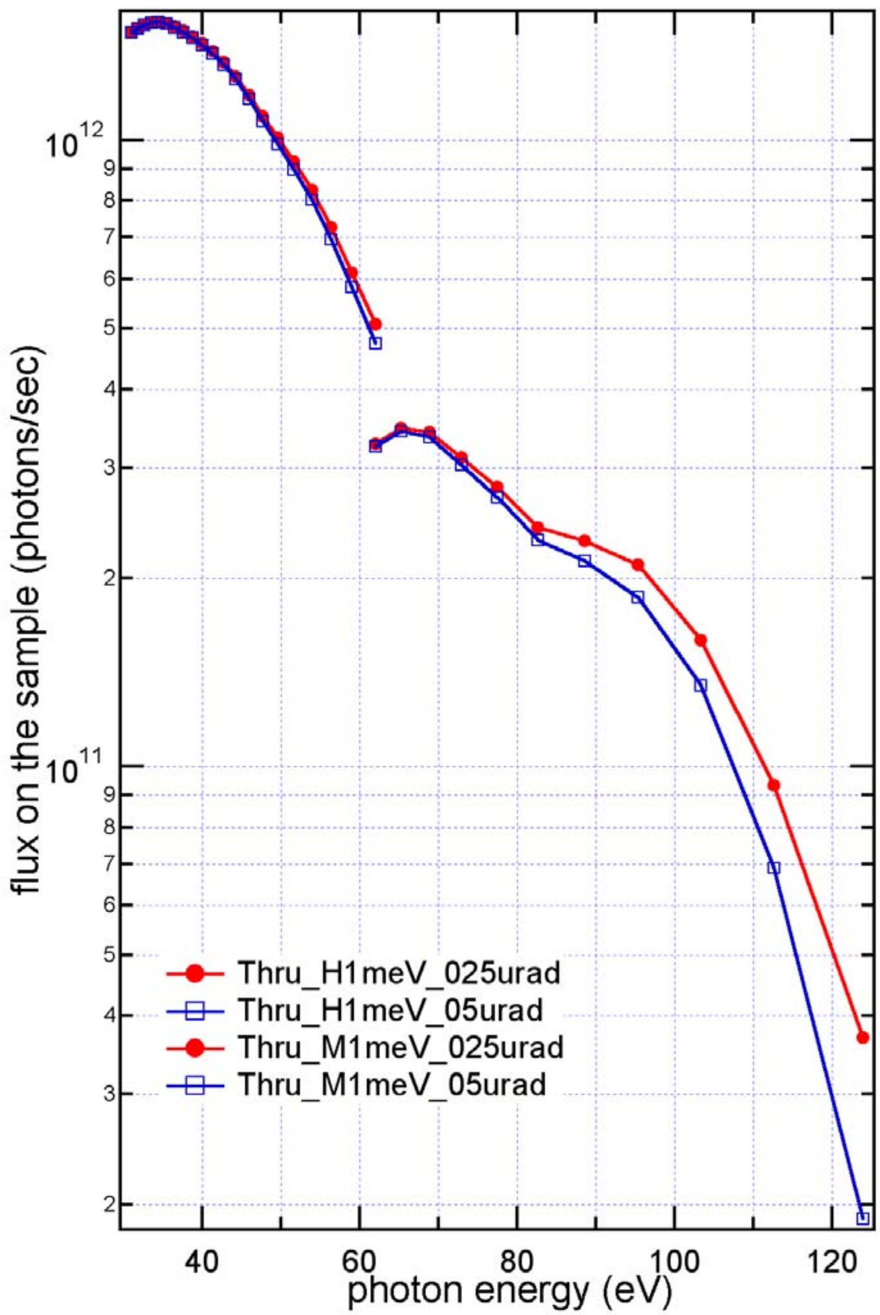


Figure 15: Flux on sample with resolving power 100,000 (left panel) and 1meV energy resolution (right panel).

This is a short summary of the long “summary report”. Based on the design submitted to DOE BES, the meV resolution beamline will have following components:

Source:
An 80mm period EPU, which is still under study process.

Beamline (also see table in Appendix in long summary report):
1. M1: horizontal deflection/horizontal focusing mirror (cylindrical) which focuses tangentially on entrance slit. Footprint is (@15eV) 500mm (L) by 15mm (W).
2. M2: horizontal deflection/vertical focusing mirror (cylindrical) which focuses sagittally on the entrance slit. Footprint is 60mm (L) by 20mm (W).
3. M3: pre-mirror (plane) inside mono tank. It deflects beam 30^o. Footprint is 40mm (L) by 3mm (W).
4. G1: spherical grating with three different rulings. Total include angle is 150^o. Footprint is 80mm (L) by 4mm (W).
5. M4: horizontal deflection/horizontal focusing mirror (cylindrical, bendable) which focuses tangentially on sample. Footprint is 200mm (L) by 20mm (W).
6. M5: vertical deflection/vertical focusing mirror (cylindrical, bendable) which focuses tangentially on sample. Footprint is 250mm (L) by 8mm (W).

Endstations:
1. UV/Soft X-ray scattering spectroscopy.
2. High resolution photoemission spectroscopy.

Based on this design, the entrance/exit slits will move only by +/- 1” and the monochromator tank will move by approximately 1m. The endstatioin array will be in building 80, right against the fire shield wall.

Some concerns (partial list) regarding the meV-resolution beamline:
Undulator source (big question mark and needs to answered first…):
1. Can this 80mm period EPU be built and delivers the required performance (i.e. go down in photon energy also with full polarization control without disturbing the ring).

Heat load issue (uncertain with ALS upgrade):
2. At 15eV, total power radiated by 80mm undulator is approximately 1.8kW and the forward radiated power in central cone is around 160W (calculation based on regular 80mm undulator with 25 periods). How to avoid heating the mirror tank (known issue in BL9.0, now no space for blocking out the radiation)?
3. The calculated power loading might be off by a factor of ~7, i.e. the first optics M1 might receive (max, with total 3.3 degree deflection) ~12W/mm^2 power density. How to handle the heat load issue? With ALS upgrade, heat load issue would be even more severe.
4. The M3 mirror, which sits in the monochromator tank, is a resolution determining optics. Its slope error and surface roughness are as critical as grating. How to minimize the heat load on M3 (adopt MES monochromator design and their water cooling mechanism? Need to check their specs).
5. In MES mono, the heat load on plane mirror at 75eV ranges from (peak value) ~0.25W/mm^2 (Cff=1.25) to ~0.1W/mm^2 (Cff=5). The corresponding slope error ranges from 4μrad to 1μrad. In our case, the heat load would produce (take the worst scenario that the value is ~7 times larger than quoted) ~0.5W/mm^2 and would result in ~8μrad slope error at 15eV. (This should be acceptable because of ~200,000 resolving power).

6. We need to calculate the power distribution on optics surface to properly model heat loading (ask Tony Warwick).

Overall design issue (current design, one option, see later discussion):

7. We need to check the currently existing mirror tank at BL4.0.2 just outside the shield wall. The mounting carriage should have been designed, and possibly fabricated. We need to know the mounting mechanism and dimension for optics (should be at least 400mm (L) by 100mm (W) to accept the central cone).
8. The second horizontal deflection mirror (M2) is place at a distance far enough (4.2 meters away from M1) to leave space for adjacent beamline and water cooling mechanism (~5" space behind mirror surface). This can be adjusted to bring the whole beamline closer to ALS floor. This would require detailed engineering modeling.
9. Both entrance and exit slits only need to move +/-1", but need to have great precision (for optimal focusing). High precision encoder (such as Heidenhein glass scale) can be used. We need to come up a driving mechanism for slits translation.
10. To achieve high resolution, both entrance slit and exit slit should have precision control (μm precision) for opening (prefer to have encoder feedback for slit opening). For entrance slit, additional water cooling mechanism is required.
11. The orientation of plane mirror and grating(s) need to be flipped to utilize MES monochromator tank.
12. Currently MES monochromator uses 450mm (L) by 80mm (W) by 75mm (H) water cooled plane silicon mirror. The footprint on M3 is much smaller, thus we should use same dimension for M3. But need to consider having two different coating (gold and carbon).
13. MES monochromator tank has ~7 degree rotation for grating carriage. We only need ~4.1 degree rotation. Thus it is enough to use their current design.
14. Currently MES monochromator uses one 168mm (L) by 76mm (W) by 50mm (H) plane grating with two rulings (and possibly two coatings). Tony Warwick mentioned that Zeiss can make three rulings with different coatings on same substrate. If we need to use more than three rulings, we need to modify the carriage to hold extra grating (and also the water cooling mechanism and the transverse motion needs to be increased up to ~6").
15. MES monochromator tank has approximately 100mm transverse (perpendicular to beam tranjectory) motion, which is used to change the grating. The range of motion is set by the bellows that couple monochromator tank to the beamline. In meV-resolution beamline, the monochromator tank needs to translate ~1 meter along the beam trajectory and ~100mm in the transverse direction. The driving mechanism needs to be designed.
16. Also the pumping on monochromator tank need to be worked out (dragging a huge TSP and ion pump with monochromator tank would be challenging).
17. In order to scan monochromator with steps having resolving power 100,000 (i.e. $\delta\lambda/\lambda=10^{-5}$), the angular increment of grating carriage should be better than $1.5*10^{-4}$ degree (or approximately 1/2 arc-second). This would require high precision sine bar (the increment over sine bar length should be ~$2.68*10^{-6}$).
18. The monochromator position would determine the focusing property, assuming that both entrance and exit slits are at correct position. If the monochromator position is incorrect, the aberration caused by defocusing (F_{200} term) would deteriorate the energy resolution. In order to achieve resolving power 100,000, the precision of monochromator position is around 200μm, assuming the grating illuminated length is 100mm.
19. The stability of monochromator tank (against vacuum load, seismic vibration…etc.) needs to be considered to achieve such high resolving power. Also the position of gratings relative to slits needs to be fixed irrespective to the locations of monochromator tank.

20. The beam pipe needs to penetrate the fire isolation wall. The exact location needs to be determined prior for detailed beamline design.
21. The whole endstation arrays (two fixed endstations with one user roll-up) will be sitting at Building 80. However, the floor underneath the area is hollow (right on top of building 80 machine shop, vacuum tech working area), thus supporting the weight is one major concern. For soft X-ray emission spectroscopy, vertical beam position (up to 200μm stability, as well as size of 5μm) determines the energy resolution. Thus ultra-high beam and endstation stability is required. How to couple the vibrations between Bldg 80 and ALS floor is the key factor.
22. Besides the floor constraint, the overhead space is quite limited. This limits the vertical cryostat geometry, whereas the horizontal space is limited by the adjacent walkway and fire isolation wall.

Another possibility is to move first optics into shield wall and obtain larger deflection angle there. This way, the beamline could be brought into ALS floor. The advantage is that the floor issue is solved and no need to penetrate the fire isolation wall if endstations are planned properly. Also the overhead space is large, which allows instruments to go vertically. However, the down time of current beamline 4.0.2 and extra cost need to be estimated.

Also the floor space might be enough for two endstaions plus one user roll-up. This really depends on where the endstations